NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT 1197

A STUDY OF THE CHARACTERISTICS OF HUMAN-PILOT CONTROL RESPONSE TO SIMULATED AIRCRAFT LATERAL MOTIONS

By DONALD C. CHEATHAM

1954

For sale by the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C. Yearly subscription, $10; foreign, $11.25; single copy price varies according to size --------- Price 20 cents

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Headquarters, 1512 H Street NW., Washington 25, D. C.

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A STUDY OF THE CHARACTERISTICS OF HUMAN-PILOT CONTROL RESPONSE TO SIMULATED AIRCRAFT LATERAL MOTIONS [1]

By Donald C. Cheatham

SUMMARY

Studies have been made in an attempt to provide information on the control operations of the human pilot. These studies included an investigation of the ability of pilots to control simulated unstable yawing oscillations, a study of the basic characteristics of human-pilot control response, and a study to determine whether and to what extent pilot control response can be represented in an analytical form.

The limit of the ability of a pilot to control simulated aircraft yawing oscillations that are made unstable by the introduction of a moment proportional to yawing velocity has been determined as a function of frequency, inherent damping, and control effectiveness. The ability to control is shown to be a function of the manner in which instability is produced in the system.

The control response of human pilots shows certain individual characteristics and inconsistencies that prevent any general representation of the control operations of human pilots by a single set of characteristics. However, the frequency-response characteristics of a group of research pilots experienced with the problem of aircraft oscillation control showed sufficient consistency to be represented approximately by an expression of response that reflects the response time of a human. This expression essentially presents the pilot as a constant-amplitude-ratio-derivative controller with a time lag. The studies, however, also indicated that, for other than oscillatory motions such as a statically divergent yawing motion, the pilot could adjust his control characteristics to suit the situation.

Calculations of pilot ability to control simulated aircraft yawing oscillations by use of this approximate expression of pilot control response show qualitative agreement with experimental results. This agreement indicates that it is practical, for the yawing condition, to represent pilot control response in an analytical form. For application to a specific problem, however, consideration should be given to the effects that particular conditions might have upon the response of the pilot.

INTRODUCTION

Recent advances in aircraft design have greatly improved aircraft performance, but the design trends necessary for this improvement have led to conditions that are inherently unfavorable for well-damped lateral oscillations. Many present-day military aircraft exhibit undesirable oscillatory characteristics and it has been predicted that some proposed designs will have dynamically unstable lateral oscillations.

Research has been directed toward the evaluation of the effect of these oscillations upon pilots' opinions of the flying qualities of aircraft and the determination of the pilot's ability to control dynamically unstable lateral oscillations (ref. 1). It is believed that a better understanding of both these problems could be had if some information on the basic characteristics of the control operations of pilots were known, and it would be especially helpful if the control operations of the pilot could be represented in a form suitable for an analysis of the combined aircraft-pilot system. Preliminary work has been done in this general field, as described in reference 2, but as yet there is a lack of information on the control operations in the piloting task.

The purpose of the present studies was to investigate further both experimentally and analytically the characteristics of pilot ability to control dynamically unstable yawing oscillations, to study pilot control response, and to determine whether and to what extent pilot control response can be represented in an analytical form.

Previous studies (ref. 1) indicated the suitability of using ground mock-ups or simulating devices to study pilot control operations. In the present studies two one-degree-of-freedom simulating devices, one for roll and one for yaw, were employed.

SYMBOLS

D	differential operator, d/dt
$e^{-\tau D}$	time-lag operator
F	rudder-pedal force, lb
h	gearing constant that includes control effectiveness and pilot control-amplitude sensitivity, ft-lb/deg/sec
I	moment of inertia, slug-ft^2
l	viscous-lag time constant, sec
N	control moment exerted by pilot, ft-lb
S	destabilizing moment, ft-lb/radian
$T_{1/2}$	time for yawing oscillation to reach half amplitude, sec
T_2	time for yawing oscillation to reach double amplitude, sec
t	time, sec
δ_r	deflection of rudder pedal, in.
τ	time lag, sec

[1] Supersedes the recently declassified NACA RM L52C17 entitled "A Study of the Characteristics of Human-Pilot Control Response to Simulated Aircraft Lateral Motions" by Donald C. Cheatham, 1952.

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ψ angle of yaw, deg

$\dot{\psi}=\frac{d\psi}{dt}$

Subscripts:

δ_r rudder deflection

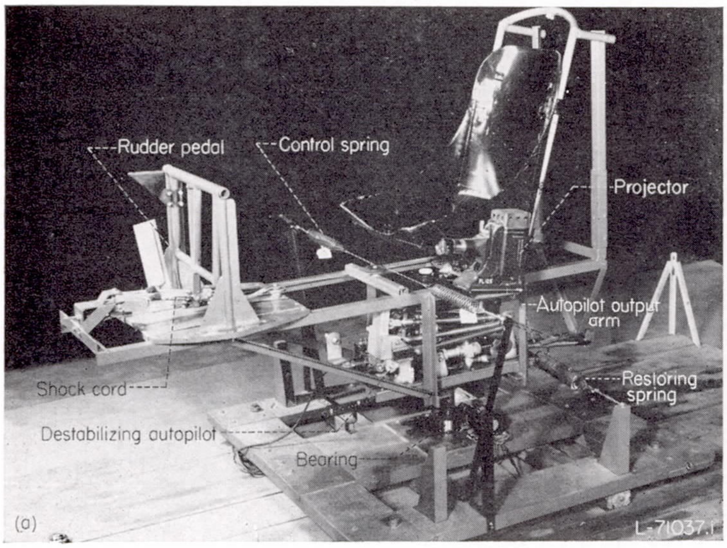
F rudder pedal force

APPARATUS

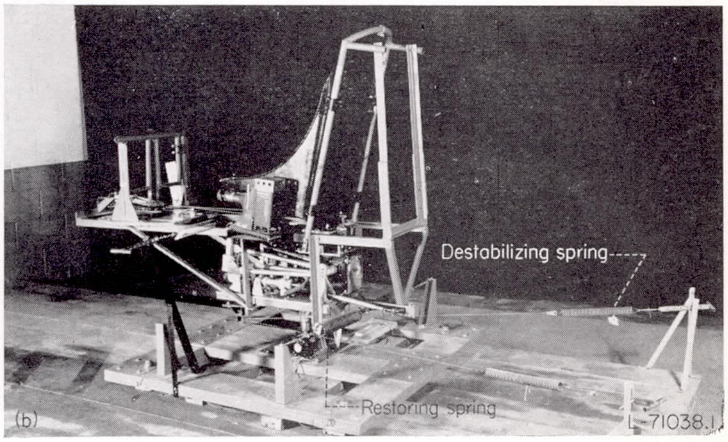
In the initial phases of the studies of human-pilot control operation and control skill, it was decided that such studies should be limited to one-degree-of-freedom motions. Inasmuch as yawing motions are known to be one of the primary causes of fixed-gun firing inaccuracies, the ability of the pilot to control the yawing component of motion appeared to be most important. Therefore, the initial investigation was restricted to a study of the pilot's control of aircraft yawing motions.

In order to facilitate the studies a ground mock-up device was built which is known as the "yaw chair." This piece of apparatus was used in the investigation described in reference 1 and, except for certain modifications, the same apparatus was used in the investigation described in the present report. As may be seen in figure 1, the yaw chair is a simple framework supporting a pilot seat and rudder-pedal arrangement and is pivoted in a bearing located directly beneath the pilot seat. The rudder pedals are connected to a "control spring" system (fig. 1(a)) in a manner that affords the pilot a means of applying yawing moments to the yaw chair. These applied yawing moments are analogous to the yawing moments applied to an aircraft by a deflection of the rudder. The spring constant of these control springs determines the control yawing-moment effectiveness that is available to the pilot. In order to give the pilot a control-force feel more nearly equal to that found in actual aircraft, a combination of shock cords is included in the control system which acts to restrain rudder-pedal movements. The pedal-force gradient created by the shock cords is great enough so that there are only minor differences in the force gradients for the three sets of control springs used. These variations of rudder-pedal force with rudder-pedal deflection are shown in figure 2. In order to make the yaw chair oscillate, a restoring spring system is connected to the yaw chair and provides the restoring forces that simulate aerodynamic stability. The control springs, however, also contribute a certain amount of restoring force so that there was a lower limit of frequency that could be obtained by varying the stiffness of the restoring springs. Therefore, it was necessary to install a set of destabilizing springs, as shown in figure 1(b), in order to produce the lower frequencies of oscillation. A schematic diagram of the destabilizing spring system is presented in figure 3 which shows how the system produces a moment in the direction of a displacement of the yaw chair from its centered position. It is the stiffness, or spring constant, of the complete yaw-chair spring system that determines the frequency at which the yaw chair will oscillate.

For the studies to be made it was desirable to provide for dynamically unstable oscillations. In order to produce this condition a moment must be introduced to the system that has an effective component 90° out of phase with the yawing displacement. Such a moment can be obtained by introducing forces proportional to the yawing velocity $\dot{\psi}$ or proportional to the time integral of yawing displacement $\int\psi\,dt$. These two methods were originally believed to give similar results, and because the latter method required simpler apparatus it was used in the investigation described in reference 1. The results of reference 1, however, showed a variation with frequency that indicated that the pilot's ability to control yawing oscillations decreased with decreasing frequency below a frequency of 0.8 cycle per second. This result was somewhat different from that which had been expected and was thought to be associated with the method of producing the instability. Thus, the desirability of the present tests in which instability is obtained by the introduction of a moment proportional to yawing velocity



(a) General view.
FIGURE 1.—Yaw-chair installation.



(b) Yaw chair with destabilizing springs attached.
FIGURE 1.—Concluded.

$\dot{\psi}$ was indicated. Essentially the difference in the two methods is that, in the case in which the destabilizing moment is introduced proportional to $\int \dot{\psi}\, dt$, the pilot has to control the yaw chair back to its exact centered position or else a moment will be introduced that tends to re-excite the oscillation; whereas, in the case in which the destabilizing moment is introduced proportional to $\dot{\psi}$, the pilot has only to stop the motion of the yaw chair at any position to stop the introduction of destabilizing moments.

The present method of producing an unstable yawing oscillation was made possible by installing a form of autopilot that is sensitive to yawing velocity on the framework of the yaw chair directly beneath the pilot's seat (fig. 1 (a)). The essential workings of this system are shown in the schematic diagram of figure 4. As the yaw chair swings in the direction indicated, the autopilot senses the yawing velocity and produces the indicated displacement of the output arm which in turn deflects the bell crank and results in an increased yawing moment in phase with the yawing velocity. The gearing of the autopilot could be controlled so that any desired damping from a slightly stable to a highly unstable condition could be obtained. The frequency-response characteristics of the autopilot for a typical condition are presented in figure 5 and show that, for the range of frequencies covered by the present tests, the performance of the autopilot satisfactorily approximates the ideal performance which would give zero phase angle and a constant-amplitude ratio with respect to $\dot{\psi}$.

In order to provide a reference point for the pilot, a projector, attached to the side of the chair, projects a reticle

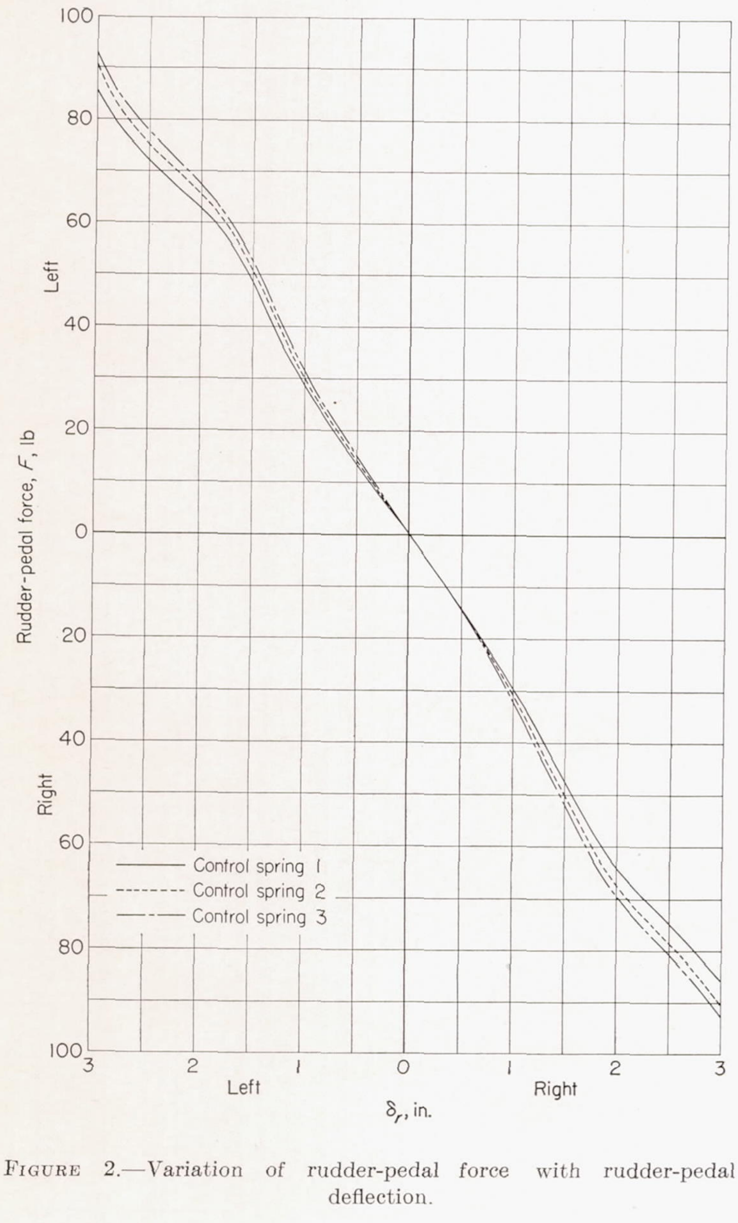


FIGURE 2.—Variation of rudder-pedal force with rudder-pedal deflection.

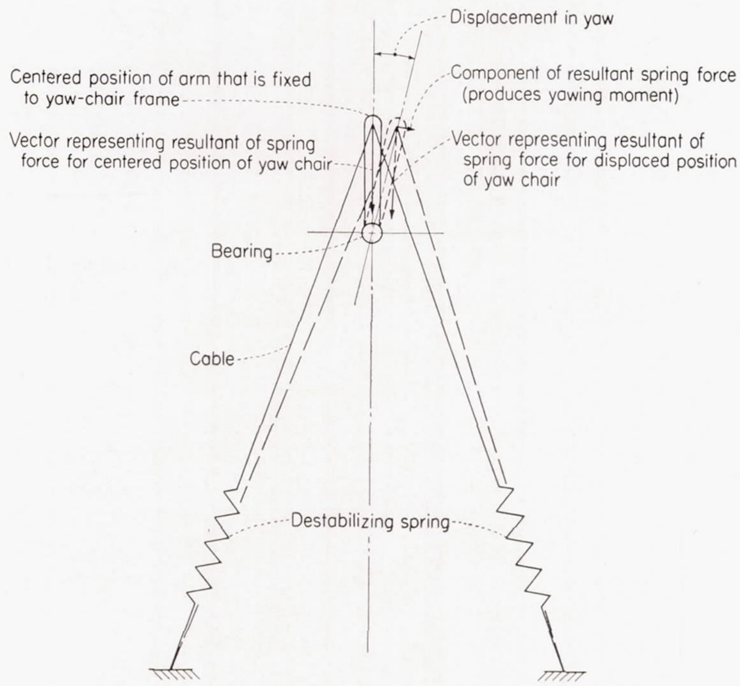


FIGURE 3.—Schematic diagram of destabilizing springs showing how the springs exert a moment in the direction of a yaw-chair displacement. Change in spring extension due to displacement of yaw chair is small in comparison to preset spring extension.

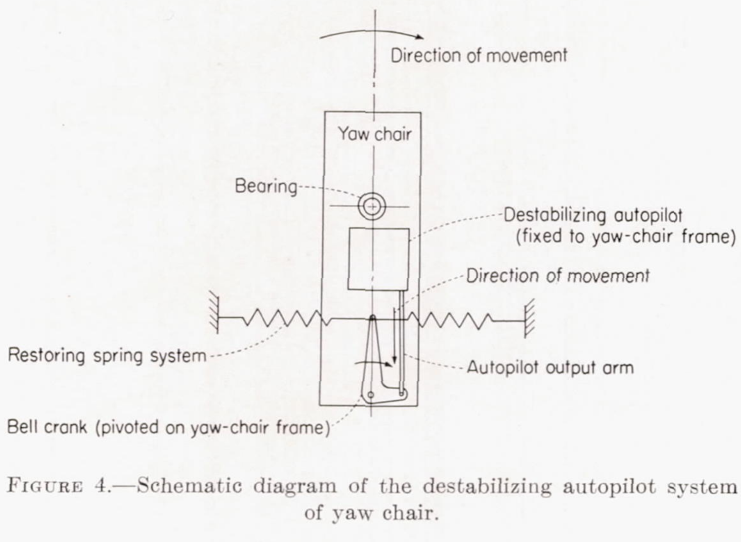


FIGURE 4.—Schematic diagram of the destabilizing autopilot system of yaw chair.

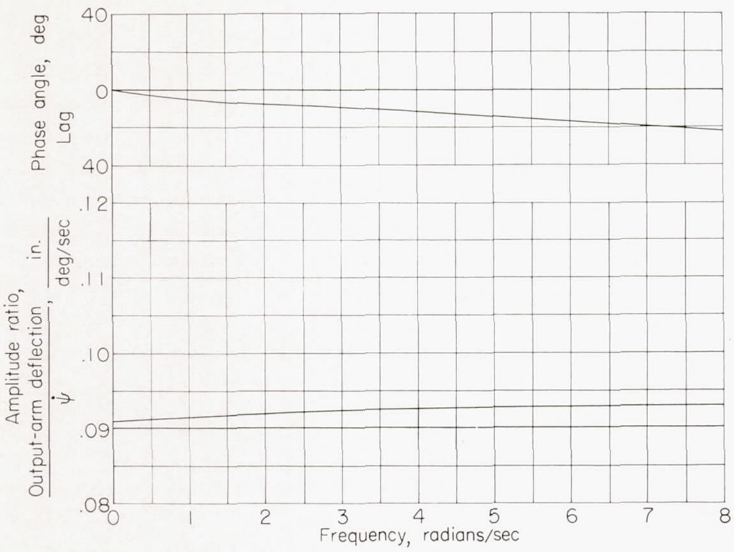


FIGURE 5.—Frequency response of the destabilizing autopilot system of yaw chair for a typical condition.

on a screen in front of the pilot. A point is marked on the screen that corresponds to the position of the reticle at zero yawing displacement.

In order to broaden the scope of the pilot-control-response studies, another device was constructed so that aircraft rolling oscillations could be simulated. This simulator, known as the "roll chair," is shown in figure 6. The roll chair is essentially similar to the yaw chair except for its plane of freedom. It, too, is a simple framework with a pilot's seat that is supported in bearings so that it is free to rotate about its longitudinal axis. A spring system also provides restoring forces necessary for an oscillatory system and a separate spring system is connected to a control wheel to enable the pilot to produce rolling moments. At the time of the completion of the roll chair, the yaw-chair studies indicated the desirability of studying the frequency-response characteristics of the pilot by subjecting him to varied-amplitude and frequency-forced sinusoidal motions and analyzing his control response. The roll chair appeared to be well suited for such studies; therefore, a driving mechanism, which can be seen in figure 6, was connected so that sinusoidal oscillations of varied frequencies and amplitudes could be forced into the simulator.

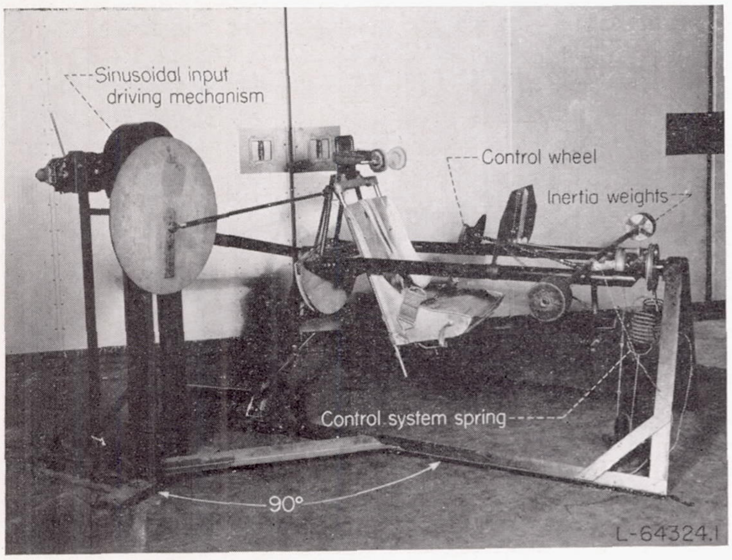


FIGURE 6.—Roll chair.

As an aid to the studies made with the roll chair, a bench setup was employed to study human response time and the characteristics of human control response to certain types of stimulus motion, such as a step motion. This setup consisted of a large disk pivoted about its center and inserted perpendicularly to the plane of a table so that only the upper part of the disk could be seen above the table. This disk had a triangle painted at a point next to the outer edge so that the apex pointed toward the center of the disk. The subject was provided with a control wheel which was linked directly with a pointer so that by turning the control wheel he could line up his pointer with the apex of the triangle painted on the disk. It was possible for the disk to be moved in a variety of patterns and the objective of the subject was to keep his pointer as closely alined as possible.

Standard NACA recording instruments were used in all three apparatus units to record the control response of the subject and the motions of the simulator or the input disk.

TESTS

The tests were divided into two phases: The first was concerned with determining the ability of pilots to control simulated aircraft yawing oscillations and the second was concerned with determining the characteristics of the control response of the pilot. These two test phases were, in part, conducted simultaneously.

For the first phase of the testing, six experienced research pilots attempted to control simulated yawing oscillations of varied frequency and inherent damping with varied control effectiveness. The frequency of oscillation was varied from zero to about 1.1 cycles per second; the inherent damping, from a slightly stable condition to a highly unstable condition; and the control effectiveness available to the pilot, over the range presented in table I. The values of control effectiveness used are roughly comparable with those used in similar tests described in reference 1 and are presented in table I as the variation of yawing moment with rudder-pedal deflection divided by the moment of inertia of the yaw chair N_{δ_r}/I and the variation of yawing moment with rudder-pedal force divided by the moment of inertia N_F/I. Also presented in the table are values of the degrees of yaw per inch of rudder-pedal deflection $\frac{d\psi}{d\delta_r}$ and the degrees of yaw per pound of rudder-pedal force $\frac{d\psi}{dF}$. These parameters were chosen

TABLE I

VALUES OF CONTROL EFFECTIVENESS PARAMETERS OF THE YAW-CHAIR TESTS

Approx. period, sec	N_{δ_r}/I	N_F/I	$d\psi/d\delta_r$	$d\psi/dF$
Control spring 1				
2. 6	7. 6	0. 24	1. 3	0. 041
2. 4	7. 6	. 24	1. 1	. 035
1. 9	7. 6	. 24	. 70	. 023
1. 45	7. 6	. 24	. 40	. 013
1. 3	7. 6	. 24	. 33	. 010
1. 0	7. 6	. 24	. 20	. 006
Control spring 2				
2. 5	14. 2	0. 45	2. 2	0. 070
2. 3	14. 2	. 45	2. 0	. 064
1. 9	14. 2	. 45	1. 2	. 038
1. 4	14. 2	. 45	. 76	. 024
1. 2	14. 2	. 45	. 56	. 018
1. 0	14. 2	. 45	. 36	. 012
. 9	14. 2	. 45	. 27	. 008
Control spring 3				
2. 4	18. 0	0. 56	2. 6	0. 084
2. 25	18. 0	. 56	2. 3	. 071
1. 85	18. 0	. 56	1. 6	. 050
1. 4	18. 0	. 56	. 95	. 029
1. 25	18. 0	. 56	. 72	. 022
1. 0	18. 0	. 56	. 44	. 014
. 9	18. 0	. 56	. 32	. 010

because they provide a convenient means of correlating the yaw-chair system with aircraft systems.

The tests were made in the following manner: For each setup an oscillation was recorded without pilot control action to provide necessary data on frequency and damping. Then a record of the pilot's attempt to control the oscillation and bring the projected reticle to bear upon the mark indicating zero yawing displacement was taken in order to evaluate his ability to control that particular characteristic oscillation. The sequence of varying the test parameters was similar to that maintained in reference 1. Brief tests were also conducted with one pilot in which the yaw chair was destabilized statically by using the destabilizing springs and leaving off the restoring springs. The resulting yaw-chair motion, without pilot control, was a static divergence.

The second phase of testing was primarily concerned with determining the frequency-response characteristics of the human pilot. Most of the tests were conducted in the roll chair in which several pilots were subjected to oscillations of varied frequency and amplitude. The frequency-response pattern was determined by analyzing the phase-angle and amplitude relationship between the pilot's control motion and the motion of the simulator. The tests were run under two conditions of the roll chair. In one condition the roll chair was allowed to oscillate through its spring system which permitted the pilot to introduce damping; in the other condition a sinusoidal oscillation was forced into the simulator system. In the latter case the pilot could not damp the oscillation regardless of the type or amount of control that he used.

The tests of response time of humans consisted of presenting approximate step inputs and irregular inputs to six persons who were not pilots by profession and recording their attempts to keep the pointers alined. Analysis of the data was simply a matter of determining the time interval between the start of the input disk movement and the start of the controlled pointer movement.

RESULTS

EXPERIMENTAL STUDIES

Ability to control simulated aircraft yawing oscillations.—The results of the present study of pilot ability to control simulated aircraft yawing oscillations were determined by analyzing sequences of test records in which the primary parameters describing oscillatory systems (frequency and inherent damping) and another parameter describing the effectiveness of the rudder-pedal control system were varied. Time histories of a typical sequence of test runs are presented in figure 7. This figure shows the control efforts and results of the pilot in his attempt to damp oscillations in which the inherent stability is being gradually decreased. The effectiveness of his control remains constant during this sequence and except for a small effect of the destabilizing moment the period of oscillation is also constant. For each variation of inherent damping a run was recorded in which the pilot performed no controlling action in order to measure the damping and frequency characteristics of the system; a record was then made of the pilot attempting to control the same oscillation in order to evaluate his ability to do so. Figure 7 shows clearly how the difficulty of controlling an oscillation increases with increasing instability.

The results of these studies are presented in figure 8 as boundary curves separating areas describing oscillations of frequency and inherent damping such that they were controllable by the pilot from areas describing oscillations that were uncontrollable. In this figure the inherent damping of the oscillation is expressed as one divided by the time for the oscillation to diverge to twice amplitude $1/T_2$. The

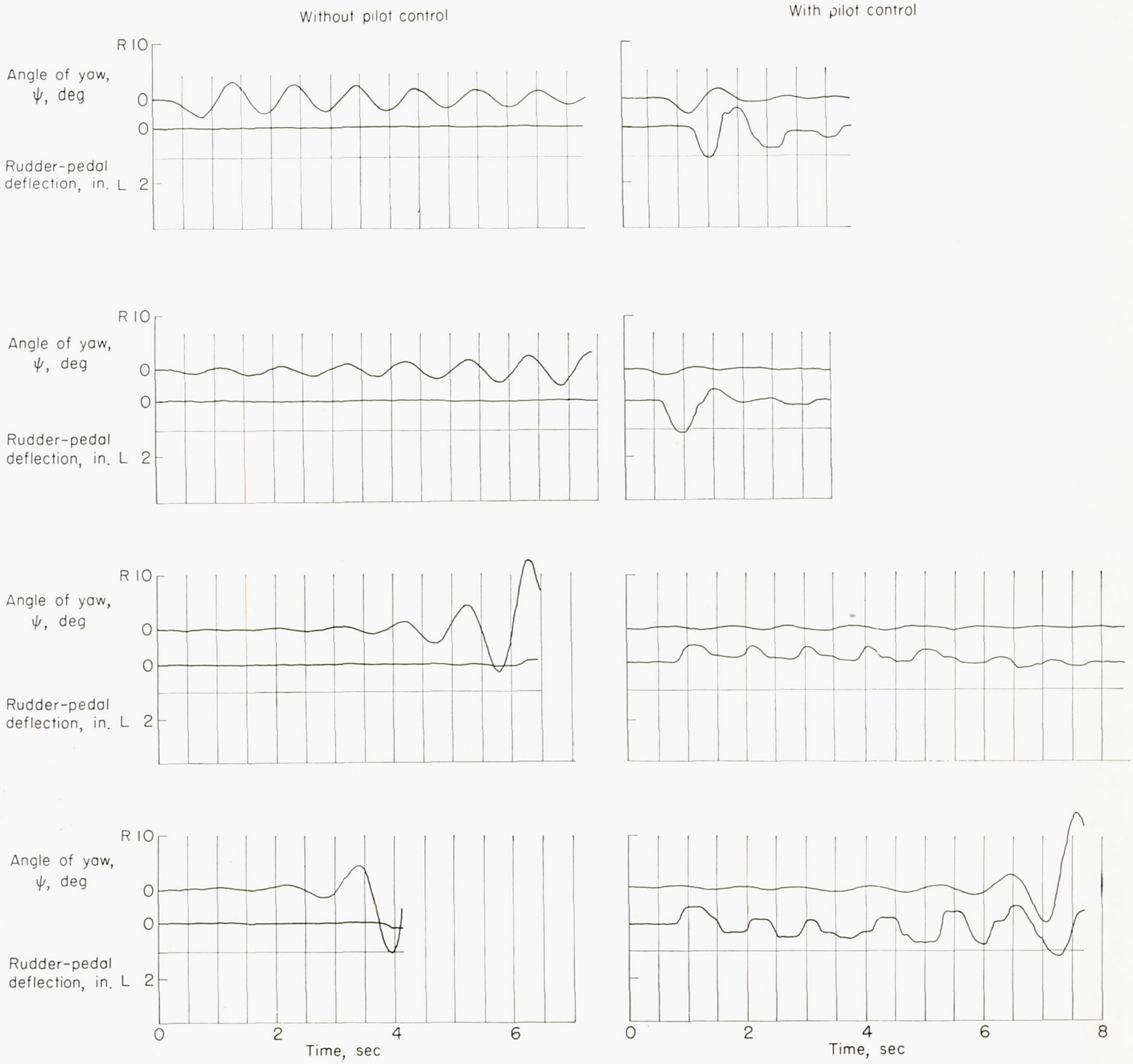


FIGURE 7.—Time histories showing sequence of yaw-chair test runs for increasing instability of the yawing oscillation. Frequency, 0.9 cycle per second; $\frac{N_F}{I}=0.56$.

fairings were made so that all data points indicating uncontrollable oscillations were included in the uncontrollable region; however, because of an overlapping of controllable and uncontrollable oscillations, some data points indicating controllable oscillations were included in the uncontrollable region.

For purposes of comparing pilot ability to control lateral oscillations where the instability of these oscillations is due to a different type of destabilization, the boundary curves determined in reference 1 are also presented in figure 8. (The symbol S represents the destabilizing moment.) These curves represent roughly the same range of control effectiveness as was used in the present studies but the destabilizing moment was introduced proportional to $\int \psi \, dt$. These two sets of curves show qualitative agreement in shape and location in the range of frequency above 0.8 cycle per second. Note that the curves from reference 1 are extrapolations in the frequency range above 1.05 cycles per second. At frequencies below 0.8 cycle per second the boundary curves of reference 1 show that the pilot could control less instability as the frequency was decreased; whereas the present tests show that the pilot could control a slightly greater instability

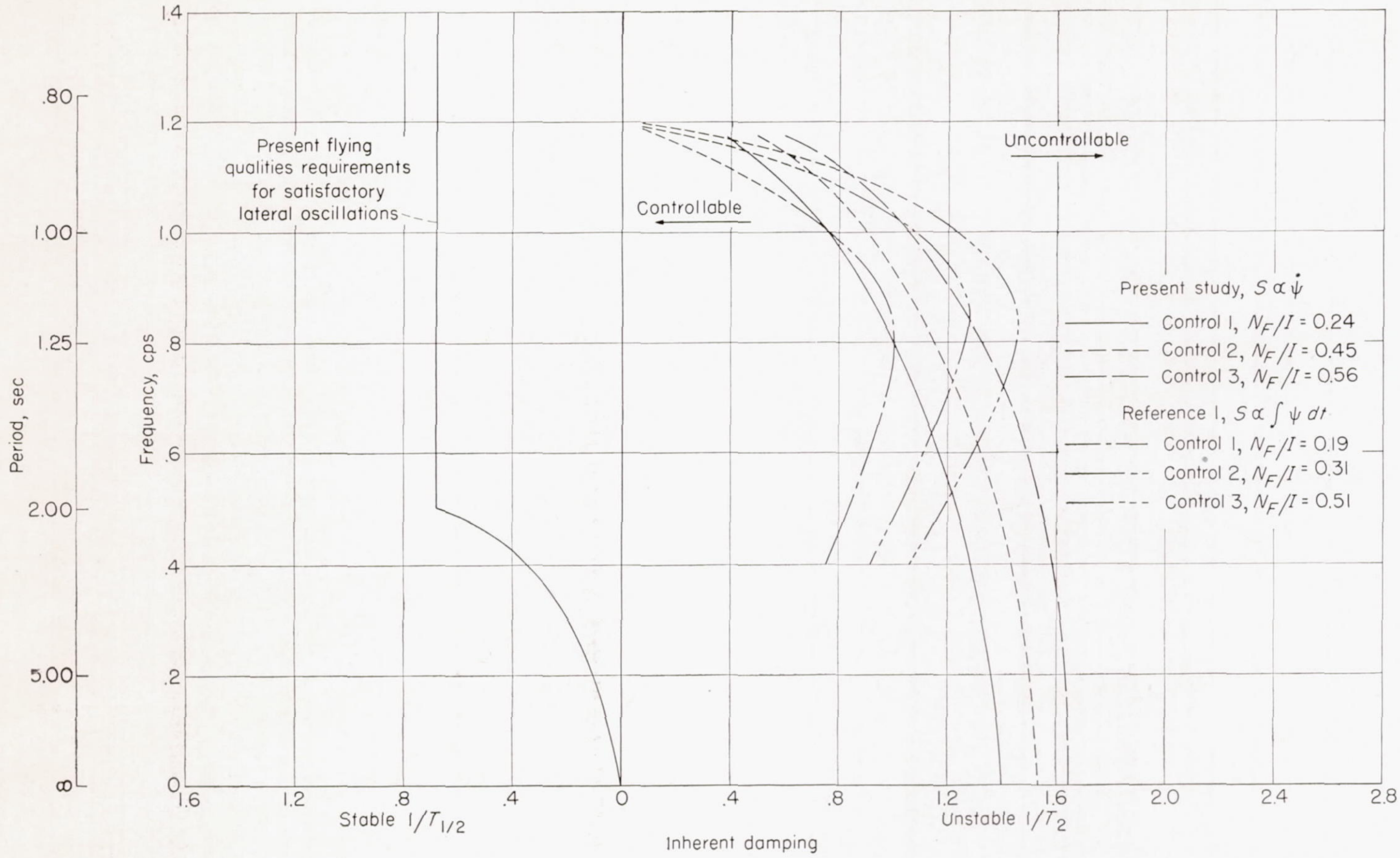
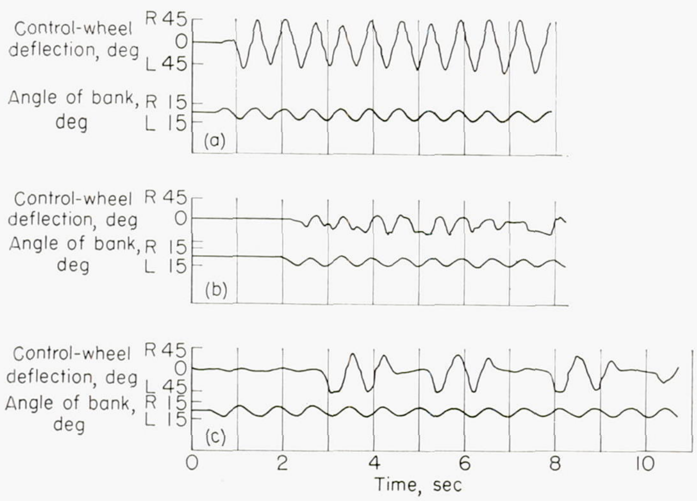


FIGURE 8.—Boundaries of pilot ability to control simulated aircraft yawing oscillations.

as the frequency approached zero. This result means that at any given frequency below 0.8 cycle per second the pilot could control a greater amount of instability for the case where destabilization was proportional to $\dot{\psi}$ than in the case where it was proportional to $\int \psi\, dt$. Also included in figure 8 is a curve representing the present Air Force-Navy flying-qualities requirements (refs. 3 and 4) for satisfactory lateral oscillations which shows that there is a large range of oscillation characteristics between those that are considered satisfactory and those that are at the limit of pilots' ability to control in the present tests. It is interesting to note that the requirements for satisfactory oscillations are based only on period and damping, and the present tests indicate that factors other than period and damping are important in determining boundaries for controllable oscillations. Although the two cases are not comparable, there is an indication that perhaps factors other than period and damping may influence boundaries for satisfactory oscillations.

In the tests conducted with the yaw chair set to perform a static divergence (static instability), it was found that with control springs 1 and 2 (see table I) the pilot could control divergences having a value of $\frac{1}{T_2}=3.3$. This value of $1/T_2$ represents a much more unstable condition than the pilot could control at zero frequency in the case where the yaw-chair motion was destabilized by a moment introduced proportional to $\dot{\psi}$ and emphasizes the fact that the ability of the pilot to control unstable simulated aircraft motion is a function of the destabilizing system.

Determination of pilot-control-response characteristics.—Concurrently with the studies conducted with the yaw chair to determine the ability of pilots to control simulated yawing oscillations, studies were being made of pilot control response to rolling and yawing oscillations. The first characteristic that was apparent in these studies was the difference in response patterns performed by different pilots. These differences were especially evident in the initial roll-chair test records of the pilots and were frequently evident during responses to relatively high frequencies of oscillations throughout the tests. Figure 9 illustrates the differences found in the control response of three pilots (pilots A, B, and C) to forced-rolling oscillations of a frequency of about 1.25 cycles per second. It may be of importance to note that each pilot was instructed to respond to the forced-rolling oscillations in a manner similar to that he would use in a corresponding flight situation and not merely to attempt to oscillate his controls at the same frequency as the



(a) Pilot A.
(b) Pilot B.
(c) Pilot C.

FIGURE 9.—Control response of three pilots to forced sinusoidal rolling oscillations. Approximate frequency, 1.25 cycles per second.

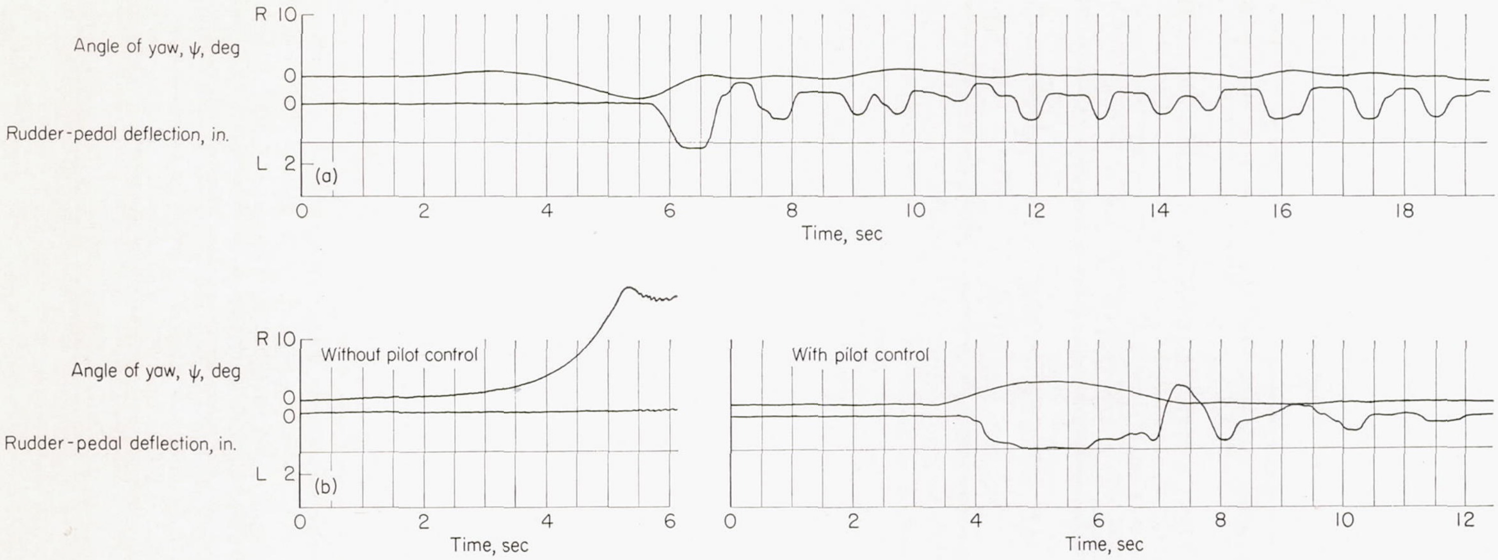
oscillation. The control response of pilot A is predominantly a smooth continuous wave form, much like that which would be expected of an autopilot. Pilot B tried to limit his response to applying control every other half-cycle. In this way, he applied control predominantly to the left. He apparently felt that by this procedure he could maintain the desired phase relationship with the oscillation; however, the result was an irregular and inconsistent response. The response of pilot C is approximately a smooth wave form but has the additional characteristic of being intermittent. The pilot observed the oscillation for several cycles and apparently determined a programmed type of control movement designed to eliminate the oscillation. The significance of these differences in pilot response patterns is that no one set of characteristics can rigorously represent pilot response. Any calculations involving pilot control response should make use of a set of characteristics applicable to the type of motion to be controlled. The results obtained still can be viewed only as an approximation.

Additional general characteristics of pilot response that were determined by an inspection of the roll-chair and yaw-chair test records were: (1) a type of nonlinearity where the amplitude ratio of control deflection to yawing displacement became greater as the amplitude of the displacement became small, and (2) an ability of the pilots to adjust their control response to fulfill the requirements of the situation. These characteristics are illustrated in the test records presented in figure 10. A case of nonlinearity of control response is shown in figure 10 (a). It can be seen that the pilot readily damps the oscillation to small amplitude but the amplitude of the pilot's control response does not decrease with a corresponding rapidity. In fact the pilot continues with appreciable control deflections at times when the trace representing yawing displacement shows a barely perceptible movement. The sensitivity of the pilot is increased to a point where he is supplying a large restoring moment which causes a short period movement. This situation is analagous to an "on-off" type of servomechanism such as is used on wind-tunnel balance beams.

The test record presented in figure 10 (b) shows a case in which the pilot is confronted with a static divergent condition of the yaw chair. This type of motion presents an entirely different problem of control to the pilot in that he has to supply a moment in phase with displacement. As can be seen in figure 10 (b) the pilot senses the control requirements and is able to alter his response characteristics in a manner to control the motion.

Frequency response.—From records such as that presented in figure 9 (a), the frequency response of the pilot to rolling oscillations was studied. For the phase-angle analysis the sense of direction used was such that when the pilot's control deflections opposed the displacement of the simulator the pilot is said to be in phase, or when the pilot's control is in the same direction as the displacement he is said to be 180° out of phase. It was found that the phase-angle relationship of the pilot's control response to the rolling motion was inconsistent at any given frequency. This inconsistency covered a rather narrow band of phase angles in the lower part of the frequency range; however, as the frequency increased the inconsistency of phase angle also increased until, at a frequency slightly higher than 1 cycle per second, the inconsistency covered the entire phase-angle range of $\pm 180°$. It is believed that the testing method is responsible for much of this inconsistency of phase angle because it deprived the pilot of ability to sense the effect of his control actions. Since the oscillations were being forced into the simulator, the pilot's control had no effectiveness and consequently the pilot did not have any indication that his control was being applied correctly. As expressed by one pilot this is a "frustrating situation" and it is natural for the pilot to vary his control movements in an effort to seek an effective manner of control. In addition to this inconsistency of phase-angle variation, it was apparent that some of the pilots were developing an ability to perform a rhythmic motion with the controls that enabled them to respond to oscillations of considerably higher frequency than was indicated to be probable by the experimental yaw-chair tests. Examples of test records showing this "rhythmic control" response are shown in figure 11. In figure 11 (a) the pilot is maintaining a smooth response at frequencies of as high as 2.5 cycles per second.

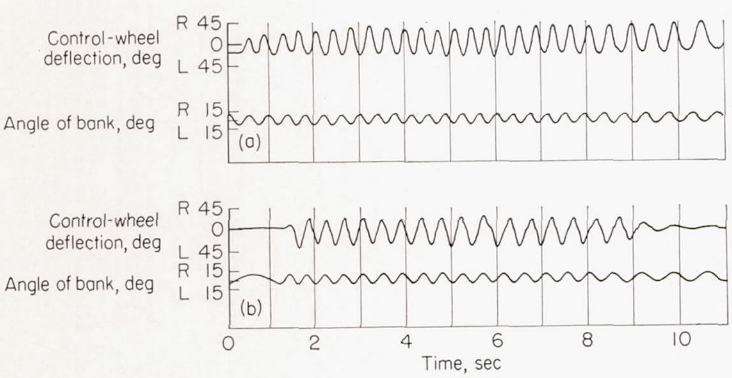
In figure 11 (b) the pilot is also maintaining a smooth response at a frequency of about 2 cycles per second and shows the ability to adjust his rhythm slightly so that his control response is approximately at the desired phase angle. In both of these cases it is believed that the pilot's ability to respond at these high frequencies results from his opportunity to estimate quickly the approximate frequency



(a) Test in which the pilot shows a type of nonlinearity of control response.

(b) Pilot controlling a static divergent condition of the yaw chair. $\frac{N_F}{I}=0.24$.

FIGURE 10.—Time histories from yaw-chair tests showing specific pilot-control-response characteristics.



(a) Example A.
(b) Example B.

FIGURE 11.—Examples of pilot rhythmic control response to high-frequency forced-rolling oscillations.

required of his response and then to sense the difference in the rhythm of his control response and the oscillation so that he can increase or decrease his frequency to make it correspond. His ability to respond would obviously deteriorate if the motion were irregular. Although such data are indicative of a type of human-pilot control response, it is apparently representative only of the specific condition of a simple periodic motion and should not be considered in a generalized expression of pilot frequency response.

Because of such deficiencies as the pilot's control being inconsistent when he has no indication that his control is being applied correctly and the existence of conditions favorable for rhythmic control response, the method of using sinusoidal input forced oscillations to study pilot frequency response is not well suited for that purpose. A point worth noting is that pilot frequency response apparently can be determined only for the case where he can sense the effects of his control. This situation implies that his response will be affected by his control success and will be dependent upon the type of motion that he is attempting to control. Therefore, it was desirable to utilize some method of determining pilot frequency response wherein the pilot control operations would be effective in the task performed and the characteristics of the motion to be controlled would be other than simple periodic motion. From the tests conducted with the yaw chair a number of records were available in which the oscillation characteristics approached the boundary of pilot ability to control and therefore the motions were more or less self generating; at the same time, however, the control moments exerted by the pilot were great enough to alter appreciably the periodic yawing motion of the simulator. The result was an irregular variation of both yawing displacement and control position, as illustrated by the examples of test records shown in figure 12. By harmonically analyzing both the variation of yawing displacement and the corresponding variation of pilot control displacement, it is possible to determine the frequency-response variation of the pilot in controlling the yaw chair. The theory of this type of analysis is given in reference 5. Such an analysis effectively eliminates the deficiencies that are believed to be present in this particular application of the steady-state sinusoidal-oscillation method.

Several of these test records were harmonically analyzed and the resulting pilot frequency response is presented in figure 13. The data presented in figure 13 (a) came from an analysis of three records by the same pilot (pilot D) in which a different control effectiveness was used for each run. There is scatter in the data from all three of the records

analyzed but this scatter was not considered large in view of the inconsistencies that are to be expected in the response patterns of human pilots. The phase-angle variation shows a gradual decrease from about 180° phase-angle lead at zero frequency to 0° at a frequency of about 7.0 radians per second. The decrease is more rapid in the frequency range up to about 2.0 radians per second and it is believed that the large phase-angle lead in this region is the result of the pilot acting so as to reduce the restoring forces in the system to slow the return of the chair from a displacement. It also may be of importance to note that, in most of the records suited for this type of analysis, the natural frequency of the yaw chair was about 4.0 radians per second and the ampli-

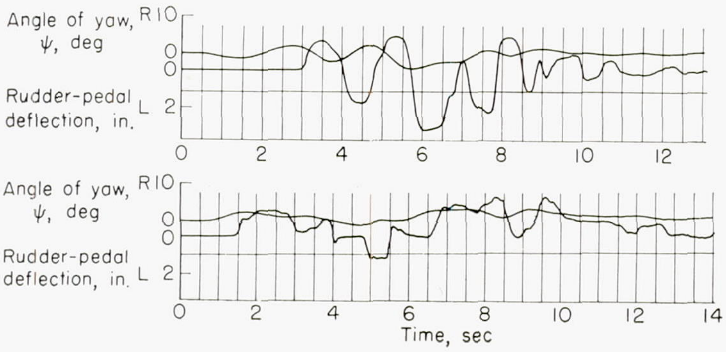
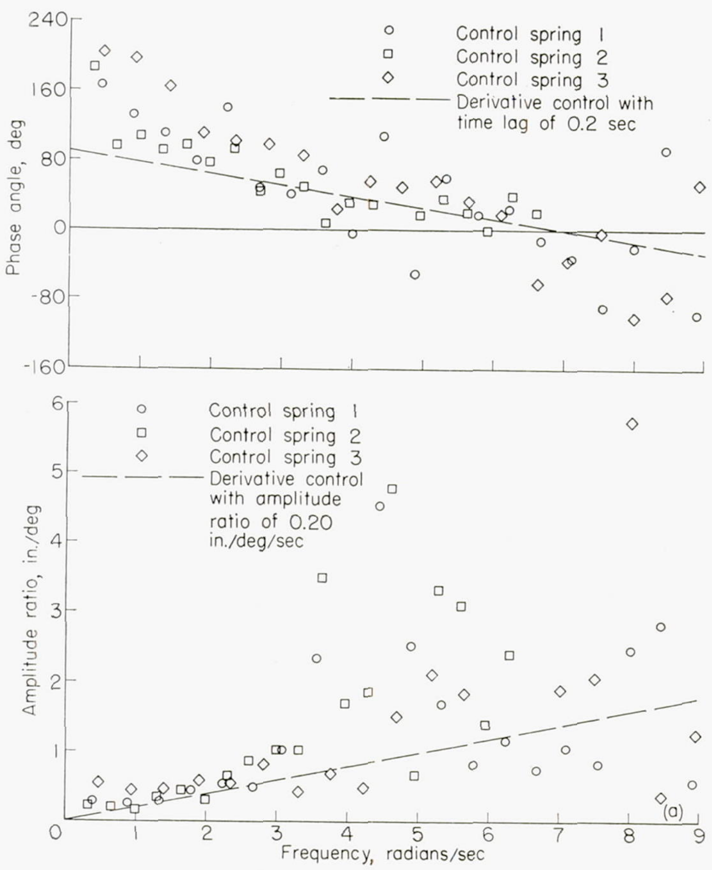
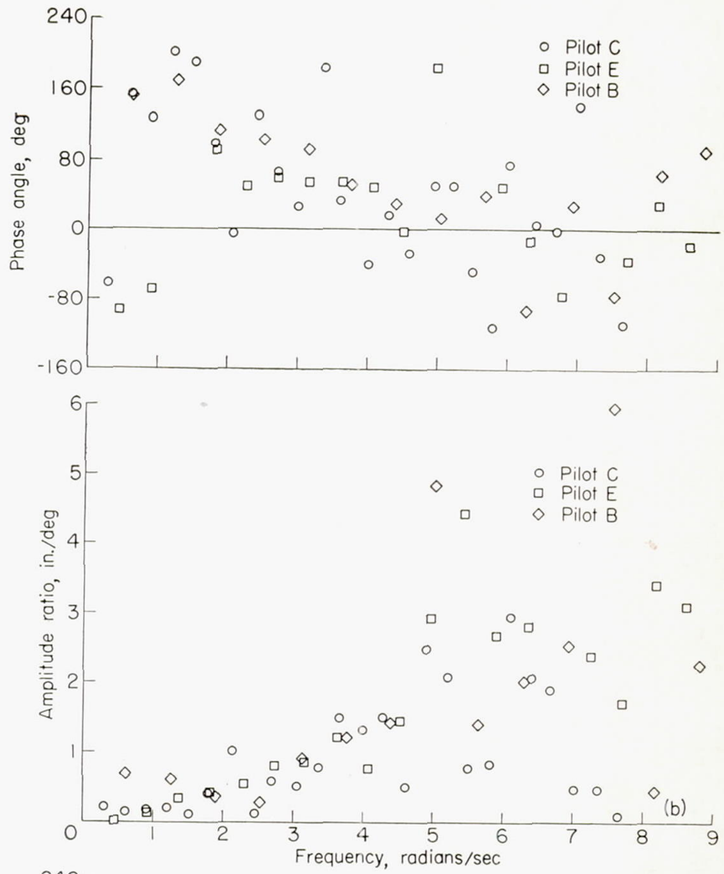


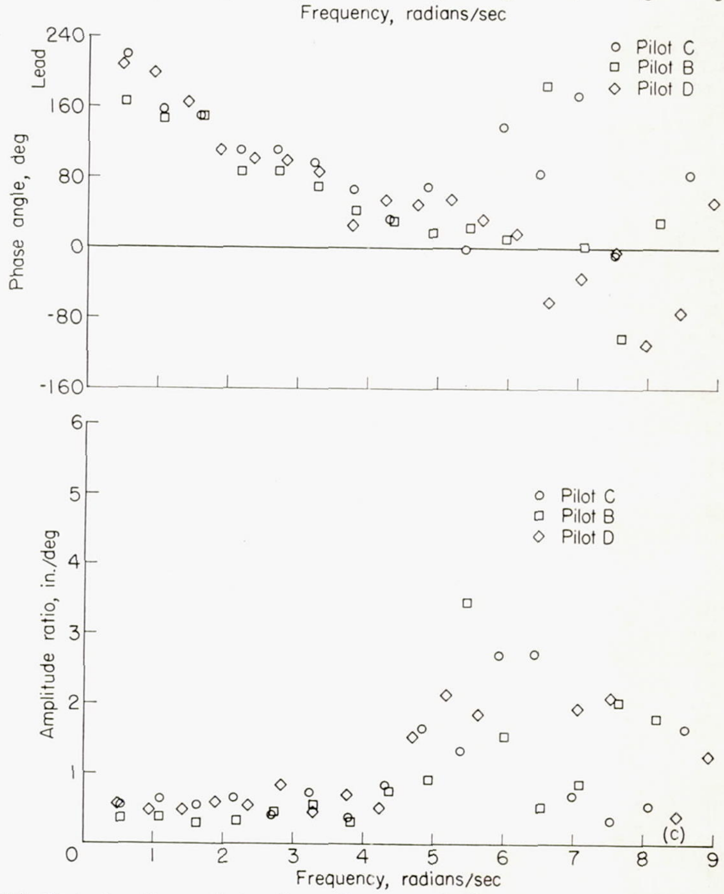
FIGURE 12.—Examples of yaw-chair test records that were harmonically analyzed to determine pilot-control frequency response to simulated aircraft yawing motion.



(a) Data for one pilot (pilot D) where three different values of control effectiveness were available.

FIGURE 13.—Frequency-response data obtained from harmonic analyses of yaw-chair test records.





(b) Data for three pilots where the control effectiveness available was the same in each case. $\frac{N_F}{I}=0.45$.

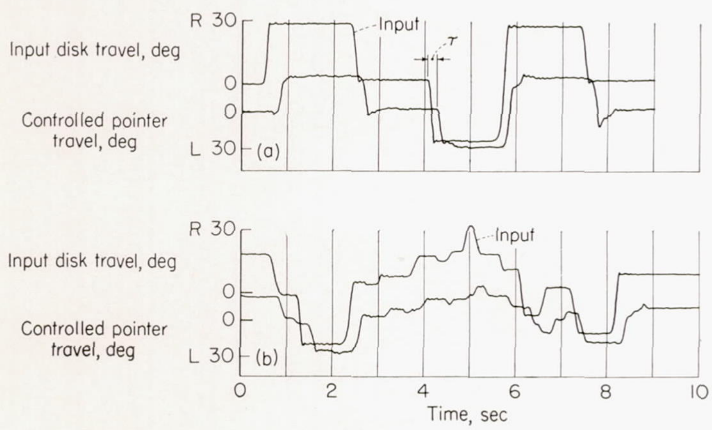
(c) Data for three pilots where the control effectiveness available was the same in each case. $\frac{N_F}{I}=0.56$.

FIGURE 13.—Concluded.

tude of the harmonics representing the low frequencies of oscillation was probably small so that the pilot was not particularly concerned with controlling those harmonics. Had the situation required that the pilot oppose the motion at the lower frequencies, it is believed that he would have no difficulty in doing so. If the data points at the lower frequencies are disregarded, a variation of phase angle that would correspond to a simple derivative response with a constant time lag of about 0.2 second would give an approximate fairing of the data points. The variation of control-response amplitude ratio was quite erratic in the higher part of the frequency range covered; however, a trend of an increasing amplitude ratio with increasing frequency is well defined. If this trend were linear, it would correspond to a derivative-control-response amplitude ratio of constant value. An attempt was made to analyze further the amplitude ratio of the control response given by the pilot by a sampling process in which instantaneous values of yawing velocity and corresponding control deflections were measured in numerous instances throughout the test records. The amplitude ratio $\delta_r/\dot{\psi}$ was determined from each set of these measurements. There was some inconsistency in control-response amplitude ratio thus obtained but on the average this method gave a value of 0.20 inch of rudder-pedal travel per degree of yaw per second. This variation of derivative control response is equal to the variation of proportional control indicated by the dashed line presented on the amplitude-ratio plot of figure 13 (a). This amplitude-ratio variation appears to be too conservative to be considered a good fairing of the data points but does substantiate the indicated trend.

Figures 13 (b) and 13 (c) each represent data for three pilots having the same control effectiveness available. These figures show essentially the same variations as in figure 13 (a) and are presented only to show the consistency of analysis.

Response time.—By use of the movable disk and pointer apparatus, previously described, the response time of six persons was studied. An example of the test runs is shown in figure 14 (a). The response time varied from about 0.2 second to about 0.4 second with the average being about 0.25 second. Additional runs were made in which the subjects responded to irregular inputs such as can be seen in figure 14 (b). Note that in figure 14 (b) if the controlled



(a) Response to approximate step inputs.
(b) Response to irregular inputs.

FIGURE 14.—Response of a human trying to keep a pointer alined with another pointer located on a movable disk.

pointer-travel variation was advanced in time about 0.2 second, it would reflect practically all the large movements of the input disk. This result was characteristic of all the subjects and indicates that their response time to an irregular, but often moving, input might be slightly less than their response time to approximate step inputs, where the time between input movements is sufficient for the pilot control movements to settle down to constant position. This 0.2-second time lag is consistent with the frequency-response phase angle variation representing a derivative control response with a 0.2-second constant time lag that was used to approximate the frequency-response data points.

ANALYTICAL STUDIES

Calculations of pilot ability to control simulated aircraft lateral oscillations.—In order to provide a more thorough investigation, the problem of determining pilot-control-response characteristics and ability to control lateral oscillations was also studied analytically. Two approaches to the problem were made: one in which initial analytical expressions of pilot control response were assumed after qualitative analysis of some yaw-chair test records performed prior to the experimental frequency-response studies, and the other in which an analytical expression representing the law of pilot control response indicated by the frequency-response data presented in figure 13 was used to calculate the control boundaries of the pilot.

Calculations from assumed laws of pilot response.—From a general inspection of the problem of oscillation control, it can be seen that, in order to control an unstable oscillation, the pilot must introduce a moment that has a component, 90° out of phase with the oscillation, of sufficient magnitude to neutralize any destabilizing moments. The pilot could well satisfy the phase-angle requirements if his control were proportional to yawing velocity $\dot{\psi}$. The data presented in reference 1 indicated that such an assumption was reasonable, but that an additional factor should be included in any expression of pilot control response to effect the apparent deterioration of the pilots' response at comparatively high frequencies. The assumption was made that the control response of the pilot would be proportional to $\dot{\psi}$ but with either a constant time lag, a viscous lag, or a combination of these two lags. The assumed laws of control can be expressed by the equations:

$$N=hD\psi_e^{-\tau D} \tag{1}$$

$$N=\frac{hD\psi}{1+lD} \tag{2}$$

$$N=\frac{hD\psi_e^{-\tau D}}{1+lD} \tag{3}$$

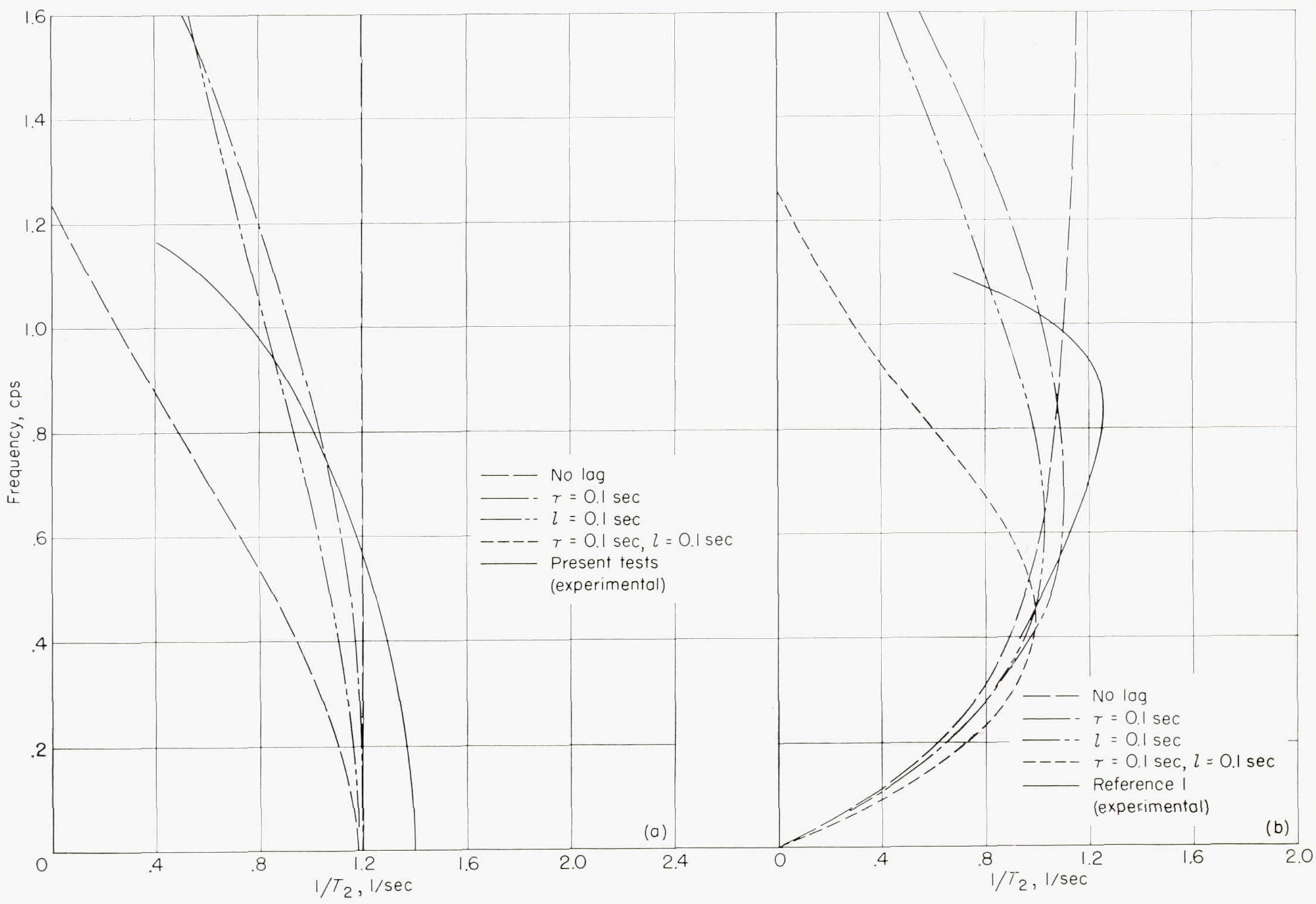
A brief analysis of some of the test records taken in the tests of reference 1 indicated that, for a given control arrangement, the control-response amplitude ratio of the pilot was approximately proportional to yawing velocity. The analysis indicated that the pilot used different response amplitude ratios for different control-effectiveness arrangements, the trend being to use the highest ratio when employing the control effectiveness of lowest value. For the control

arrangement corresponding to an effectiveness value of $\frac{N_{\delta_r}}{I}=11.0$, the pilots used a control-response amplitude ratio of about 0.15 inch of rudder-pedal deflection per degree of yaw per second. This combination of control effectiveness and pilot-response amplitude was used in the present analysis to calculate the value of the gearing constant used by the pilot.

In order to determine the effect of control response with constant time lag or viscous lag or both upon the pilot's ability to control oscillations, the control boundaries were calculated by use of arbitrary values of constant time lag of 0.1 second and viscous-lag time constant of 0.1 second. The control boundaries for the various assumed pilot response characteristics are presented in figure 15. The initial discussion will be concerned with the case of $S \propto \int\psi\, dt$ (fig. 15 (b)) where S represents the destabilizing moment. In addition to the curves representing boundary conditions for pilot response with the given lag factors and with a combination of the given lag factors, two other boundary curves are presented: one for the condition of no lag present in the pilot's control response, and the other for the experimental boundary from reference 1 representing a control effectiveness of $\frac{N_{\delta_r}}{I}=11.0$.

It can readily be seen from this figure that the calculated variations of the boundary of pilot ability to control simulated oscillations are consistent with the trend of the experimental curve of reference 1 to approach zero value of $1/T_2$ at zero frequency. In the frequency range below 0.5 cycle per second, the pilot's ability to control is apparently little affected by lags of the order of magnitude used in the calculations. In fact, with the destabilizing moment introduced proportional to $\int\psi\, dt$, the calculated variations with lags included indicate a slightly more effective response in this frequency region than the boundary curve for pilot response having no lag. In the higher frequency range the calculated boundaries representing either viscous or constant time lag showed the characteristic of decreasing $1/T_2$ with increasing frequency as was shown by the experimental curve, although the locations of the curves were appreciably different. The one notable difference in characteristics between the calculated and experimental curves was that the maximum values of $1/T_2$ for the calculated curves occurred at lower frequencies than in the experimental case. This result may mean that the pilot's actual response differs from the assumed pilot response in (a) increasing gearing ratio in this frequency range or (b) decreasing lag in this frequency range or (c) both increasing the gearing ratio and decreasing the lag.

Figure 15 (a) presents the calculated boundary curves for



(a) Destabilizing moment proportional to $\dot{\psi}$. $\frac{N_F}{I}=0.24$

(b) Destabilizing moment proportional to $\int\psi\, dt$. $\frac{N_F}{I}=0.31$.

FIGURE 15.—Calculated boundaries of pilot ability to control simulated yawing oscillations in which various simplified expressions of pilot control response were assumed.

the same response expressions as in figure 15 (b) but for the case where the oscillations were destabilized by a moment introduced proportional to $\dot{\psi}$. Comparison of the boundaries presented in this figure with corresponding boundaries in figure 15 (b) for the same laws of pilot control response shows that the same characteristic differences are present as were present in the experimental boundaries. This consistency is at least an indication that the pilot's response followed the same law in the two experimental cases and is a further indication that the ability of the pilot to control unstable oscillations is a function of the method by which the system is made unstable.

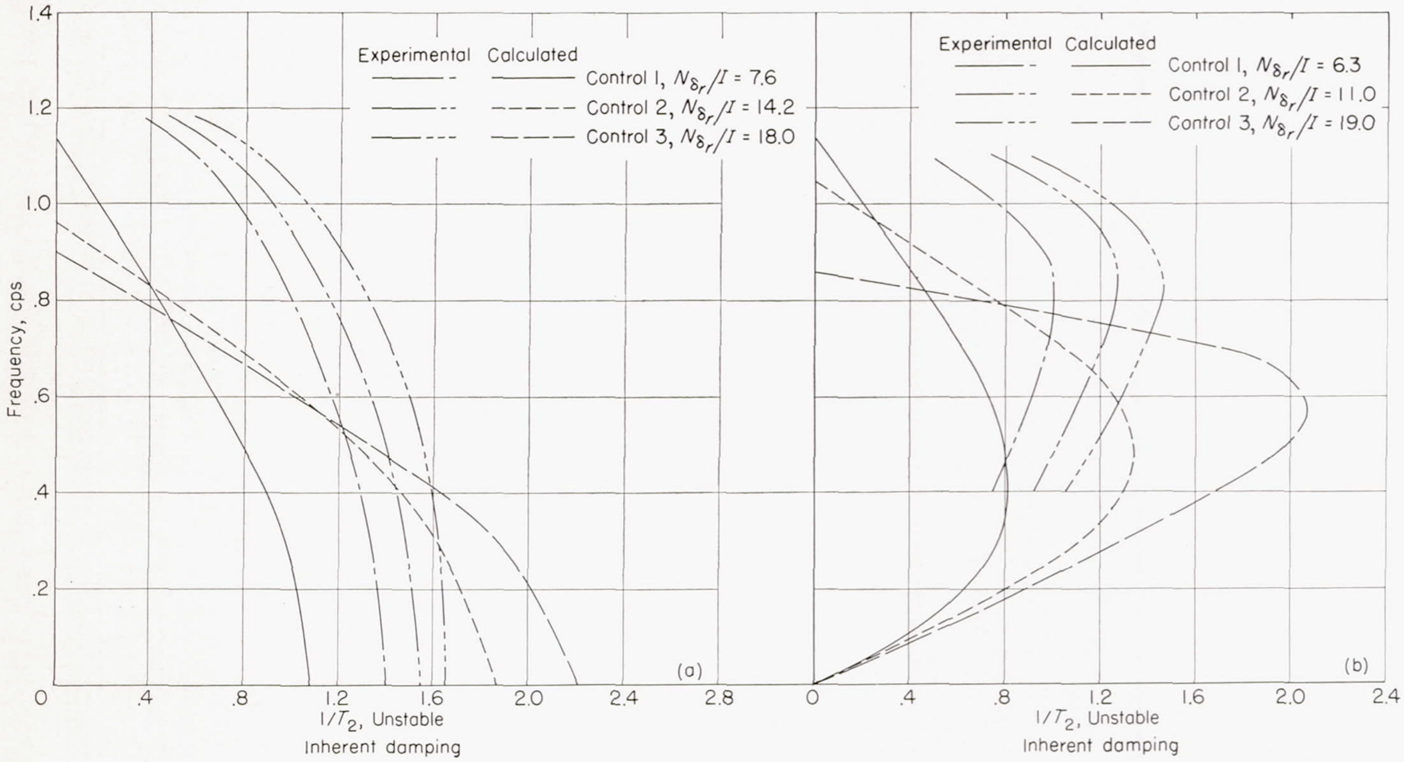
Calculations from experimental law of response.—The frequency-response data as presented in figure 13 have indicated an approximate law of control response of the human pilot while controlling unstable yawing oscillations. The dashed lines in figure 13 (a) are representative of a derivative controller of constant amplitude ratio $\frac{d\delta_r}{d\dot{\psi}}=0.20$ inch per degree per second, or $\frac{dF}{d\dot{\psi}}=5.7$ pounds per degree per second and with a constant time lag of 0.2 second. From this law of control in conjunction with the values of control effectiveness corresponding to values for the three control arrangements used in each of the experimental studies (ref. 1 and present tests), the boundaries of pilot control ability were calculated.

The results of these calculations are presented in figure 16. The boundary curves calculated by using values of control effectiveness available in the experimental tests of reference 1 for the case in which destabilizing moment was proportional to $\int\psi\,dt$ are represented in figure 16 (b), and for comparison the experimental boundaries from reference 1 are also presented. The basic characteristics of comparable experimental and calculated curves are similar, although it is apparent that the assumed amplitude ratio for the control effectiveness of $\frac{N_{\delta_r}}{I}=19.0$ is higher than the ratio actually used by the pilot. In general, the notable difference was the occurrence of maximum values of $1/T_2$ at a lower frequency for the calculated curve and also the failure of the calculated boundaries to include the higher frequency oscillations indicated by the experimental boundaries. This result indicates that perhaps the pilot maintained a better phase relationship than would be indicated by the assumed 0.2-second constant time lag.

The case of the destabilizing moment proportional to yawing velocity is presented in figure 16 (a) for calculated and comparable experimental boundaries. Essentially the same observations can be made as were made for figure 16 (b). The higher frequency range covered by the experimental curves indicates the possibility of the pilots' utilizing, to some extent, their previously exhibited rhythmic control, in which case it would be possible for them to have less control-response time lag at the higher frequencies.

DISCUSSION

It is important to note that the pilots performing the yaw-chair tests were all thoroughly familiar with the problem of controlling aircraft lateral oscillations. Also, all but one of the pilots had previous extensive practice in the yaw-chair tests described in reference 1. For this reason, the inconsistencies of response that would be expected during a learning cycle were apparently of small magnitude and, in addi-



(a) Destabilizing moment proportional to $\dot{\psi}$.

(b) Destabilizing moment proportional to $\int\psi\,dt$.

FIGURE 16.—Calculated boundaries of pilot ability to control simulated unstable yawing oscillations by use of a law of pilot-control response indicated by experimental frequency-response data.

tion, the beneficial effects of practice were believed to be at a fairly high level throughout the present test program. However, there were numerous occasions on which the yaw chair was demonstrated to pilots other than the pilots performing the test program, and it was obvious that the factors of familiarity with the problem and practice were extremely important factors affecting the pilots' ability to control simulated aircraft lateral oscillations. It is believed that the limiting frequency of oscillation to which an average pilot with practice in controlling yawing oscillations can correctly respond and which he can control with consistency is close to that limit established in reference 1 of slightly less than 1 cycle per second. Also considered as an important factor in the boundaries established in the present studies is the fact that the pilots could devote their undivided attention to the control of the yawing oscillation, an obvious advantage over actual flight conditions. In general, the test conditions were such as to bring out the maximum in pilot ability and results should be viewed with that realization.

By using analytical expressions of the pilots' control operation it was possible to calculate a rough approximation of pilot ability to control unstable oscillations. The calculated boundaries did not agree exactly with experimentally determined boundaries but it is believed that the analytical expression obtained from the frequency-response data will be valuable for certain calculations. Such a calculation would be to determine whether the pilots' control response will have a destabilizing effect on an otherwise stable aircraft system or, in the case of an inherently unstable aircraft system made stable by artificial means, to determine whether the pilot would be able to control the airplane in case of a failure of the artificial stabilization.

It should be realized that the present studies utilized test conditions which perhaps give the pilot advantages that cannot be realized in flight. For instance, it is probable that during a long flight the control requirements of an unstable oscillatory condition might fatigue the pilot to the extent that the effectiveness of his control response might diminish considerably. Also, it might be that the mechanics and dynamics of the aircraft control system would result in an appreciably different pilot control amplitude response or that the arrangement of the aircraft might be such that there is a lack of a good reference by which the pilot can sense the oscillations. In general, in the analysis of the performance of the human pilot, consideration must be given to the effect that environment might have upon the pilot response characteristics.

CONCLUSIONS

Studies of pilot control response to simulated aircraft motions have indicated the following conclusions:

1. The limit of ability of pilots to control simulated unstable aircraft yawing oscillations (single degree of freedom) where the destabilizing moment is introduced proportional to yawing velocity $\dot{\psi}$ has been experimentally determined as a function of frequency of oscillation, inherent damping, and control effectiveness.

2. A comparison with previous work showed that the ability of pilots to control yawing oscillations was also a function of the characteristics of the destabilizing element in the system.

3. The control responses of pilots to simulated rolling or yawing aircraft motions have individual characteristics and inconsistencies that prevented an exact representation of the pilots' control operation.

4. Frequency-response analysis of human pilots by the method in which sinusoidal input forced oscillations were used yielded results substantially different from harmonic analysis of irregular input and output test records. The difference was attributed to the ability of human pilots to develop a rhythmic response when controlling motions of a simple periodic form and also to the inconsistencies of the pilot's control response when his control has no effect upon the motion to be controlled. It is believed that the frequency response of the pilot obtained by the harmonic analysis of response to irregular inputs should be used for any application of pilot control response to lateral oscillations and, in addition, the pilot must be able to sense the effect of his control actions upon the motion he is controlling.

5. The frequency-response data determined by harmonic analysis of irregular input records indicated a phase-angle variation that is reflective of the response time of a human. The control-response amplitude ratio indicated that the pilots, in attempting to control unstable oscillations, responded proportionally to velocity over most of the frequency range. However, the studies also indicated that the control response of pilots may vary in accordance with the control requirements of different situations.

6. Calculation of pilot ability to control simulated aircraft yawing oscillations by using a control-response expression that approximates the experimentally determined frequency response of the pilot gave results that compare qualitatively with experimental results.

7. The use of an analytical expression to represent the control operations of the pilot in equations representing the motion of an airplane appears practical in the case of simulated yawing oscillations. In any application, however, consideration must be given to the effects that conditions particular to the application might have upon the control response of the pilot.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *March 14, 1952.*

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U. S. GOVERNMENT PRINTING OFFICE: 1955